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**SPACE
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SPACE RADIATIONS: A COMPILATION AND DISCUSSION

By

W. T. Roberts

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ABSTRACT

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The natural radiations encountered during a space mission will fall into one of five categories. There will be Van Allen belts, galactic cosmic radiations, solar winds, solar flares, and photon radiations. Each type of radiation is examined from the point of view of the Apollo program and the associated lunar logistics vehicle, but with some comments pointing to extended missions in space, to determine the importance which should be assigned to each class.

Author

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SPACE ENVIRONMENT GROUP
AERO-ASTROPHYSICS OFFICE
AERO-ASTRODYNAMICS LABORATORY

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DEFINITIONS

- rem - Relative biological equivalent (RBE) dose equal numerically to the product of the absorbed dose in rads by an agreed conventional value of the RBE. The RBE is taken with respect to a particular form of radiation effect when the standard of comparison is radiation having a LET of 3 Kev/micron delivered at a rate of about 10 rad/min.
- rad - unit of absorbed radiation equal to 100 ergs/gram.
- roentgen - unit of exposure dose of X- or γ -radiation such that the associated corpuscular emission per 0.001293 grams of air produces, in air, ions carrying one electrostatic unit of quantity of electricity of either sign.
- LET - (Linear Energy Transfer) - The energy locally absorbed per centimeter of path in air. One LET equals about 3 Kev/micron.

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SUMMARY

The natural radiations encountered during a space mission will fall into one of five categories. There will be Van Allen belts, galactic cosmic radiations, solar winds, solar flares, and photon radiations. Each type of radiation is examined from the point of view of the Apollo program and the associated lunar logistics vehicle, but with some comments pointing to extended missions in space, to determine the importance which should be assigned to each class.

I. INTRODUCTION

Radiation which will be encountered during any specific extra-terrestrial mission may be divided into five basic types. These are (a) Van Allen radiations, from particles of various energies trapped in the magnetic field of a planet, (b) galactic cosmic radiations, which are extremely high energy particles originating outside our solar system, (c) the "solar wind," which is a kinetic flow of particles from the sun varying with solar activity, (d) solar flares, which are gigantic "explosions" seen on the photosphere of the sun and which apparently cause an ejection of high energy particles, and (e) spectral irradiation, which is the photon flux from the sun and may therefore cause indirect radiation problems by ionization.

Still another type of radiation will be encountered (assuming passive shielding) which may be of more significance than any of those mentioned above. This radiation is the secondary particles produced when high energy primaries are absorbed in the shielding materials. Along with this will be X-rays resulting from bremsstrahlung. The exact amount of radiation resulting from this secondary effect is not easily calculated since it depends upon the type of material used in the shielding, the energy of the primary radiation, etc.

In the preceding paragraph, we mentioned that we are assuming passive shielding. Active shielding appears to have taken an extremely significant step forward since the development of the superconducting magnet, but since much refinement and experimentation as yet remains to be done, we may conclude that passive shielding must be used at present.

II. VAN ALLEN RADIATION BELTS

The Van Allen radiation belts were first observed by the satellite Explorer I in 1958, and its existence was shortly confirmed by Explorer III and Sputnik III observations. Professor James Van Allen had conducted both experiments on Explorers I and III and determined that the observed data indicated the existence of charged particles trapped by the magnetic field.

Over the years, the Van Allen belt has been mapped and refinements have been made in the various zones [1] until finally the picture of an inner and outer zone emerged with particles of energies listed in Table I. Table I is given in the B-L coordinate system, where B is the magnitude of the magnetic induction, and L is the equatorial distance to the dipole field line about which the particles are spiraling.

In addition to the naturally occurring radiation zones, high altitude nuclear explosions have ejected high energy particles which distort the existing zones. Fortunately, however, the artificially created belts decay rather rapidly in the outer zones leaving a more lasting nucleus of high energy particles contained within the limits of the natural radiation zone.

It has been found that vehicles in a relatively low circular earth orbit (200-600 km) will receive an insignificant amount of radiation from the Van Allen zones; however, a vehicle with an eccentric orbit or one which has a relatively high circular orbit receives a much higher flux. For example, a satellite in a synchronous orbit over the equator will be very close to the center of the outer Van Allen zone.

Methods are now under development to determine the optimum trajectories (in terms of dose rates) to be used for various mission profiles. If this method proves successful, the mission may be made more complicated due to the specification of a path to be followed through the Van Allen zones.

The Van Allen zones vary diurnally as the magnetosphere. Since on the sunward side of the earth the magnetosphere is flattened and condensed, the particles which are trapped by the magnetic lines of force are also flattened. At the nadir, however, the magnetosphere is elongated; therefore, the zones of trapped particles are also stretched.

It has been discovered that the boundary of the magnetosphere itself contains a great number of charged particles, apparently due to the flow of the solar wind.

There have been a number of theories proposed regarding how the Van Allen belts are maintained, and how they lose particles. It has been fairly well established that protons are lost to the belts by their interaction with atmospheric constituents. Table 2 shows the range which protons have in aluminum [4]. Electrons in the Van Allen belts are probably lost by scattering due to coulomb forces.

Several mechanisms have been investigated to determine how the particles are maintained in the belts. One theory [3] suggests that solar particles may be able to enter the magnetosphere at the polar regions. Such a theory could be acceptable for the outer belt, but the inner belt requires a different explanation. One possibility is that the inner belt is due to the decay of neutrons, but these may only account for the relatively high energy particles.

Since the atmospheric density in the exosphere varies markedly with the solar cycle, it should not be surprising to find the particle flux varying inversely with the solar cycle.

The Van Allen zones should be of considerable consequence as a radiation hazard to space vehicles.

TABLE 1
VAN ALLEN RADIATION BELT

Heart of Inner Zone ($L \sim 1.4$, $B \approx 0.12$, alt = 3600 km)

<u>Particle</u>	<u>Energy</u>	<u>Flux</u>
Protons	($E > 30$ Mev)	$\sim 3 \times 10^4/\text{cm}^2 \text{ sec}$
Electrons	($E > 600$ Kev)	$\sim 2 \times 10^6/\text{cm}^2 \text{ sec}$
Electrons	($E > 40$ Kev)	$\sim 10^8/\text{cm}^2 \text{ sec}$

Heart of Outer Zone ($L \sim 3.5$, alt $\approx 25,000$ km)

Electrons	($E > 40$ Kev)	$\sim 10^7/\text{cm}^2 \text{ sec}$
Electrons	($1.5 < E < 5$ Mev)	$\sim 10^4/\text{cm}^2 \text{ sec}$
Protons	($0.1 < E < 5$ Mev)	$\sim 10^8/\text{cm}^2 \text{ sec}$
Protons	($E > 1$ Mev)	$\sim 10^7/\text{cm}^2 \text{ sec}$
Protons	($E > 75$ Mev)	$\sim 0.1/\text{cm}^2 \text{ sec}$

TABLE 2
RANGES OF PROTONS IN ALUMINUM

<u>Energy (Mev)</u>	<u>Range (gm/cm²)</u>
10 ²	10.5
10 ¹	1.7 x 10 ⁻¹
10 ⁰	3.5 x 10 ⁻³

III. GALACTIC COSMIC RADIATION

The radiation with the highest energy per particle encountered in outer space will undoubtedly be the galactic cosmic radiations. Since the flux of these particles is relatively low, the radiation problem will not be as significant as for particles with lower energies and higher flux. The energies of these particles will usually exceed one billion electron volts (1 Bev) and as a result may produce secondaries which will be of more concern than the primary radiation itself.

Galactic cosmic radiation exhibits a tendency to vary inversely with the solar cycle. This has been attributed to the solar magnetic field lines which are carried out from the sun farther during higher solar activity periods. Since the cosmic ray particles are charged, they are deflected by these magnetic lines of force. As the solar activity period decreases, the "interplanetary lines of magnetic force" become weaker and the resulting deflection of particles becomes less. Thus, fewer particles are excluded from the solar system.

A variation very similar to this is the 27-day variation with the solar cycle. This is due to the reappearance of sunspots that have long lines. These interplanetary magnetic lines of force exhibit variations with the sunspot groups. Since the mean rotational period of the sunspot region is approximately twenty-seven days, the 27-day period exhibited by the cosmic rays is considered to be a direct result.

The final variation noted in the flux of cosmic rays reaching the earth is known as the Forbush decrease. The Forbush decrease is a significant decrease in flux of cosmic rays incident on the earth following a solar flare. A decrease of approximately 30% of the flux has been noted and the recovery time following the decrease is usually from one to two days. This phenomenon is considered to be caused by the ejection of a vast plasma cloud. This cloud in turn carries

magnetic lines of force away from the surface of the sun. When the cloud reaches the earth, the cosmic rays suddenly decrease due to the presence of the magnetic lines of force. At about the same time, the beginning of a magnetic storm takes place as well as the other associated geomagnetic disturbances.

Particles reaching the earth will penetrate the magnetic field to a certain depth depending upon the rigidity, R , exhibited by the particles. Rigidity is simply the ratio of the particle's momentum to its charge,

$$R = \frac{pc}{Ze} ,$$

where p is the momentum (in units of Bev/c), c is the velocity of light, Z is the atomic number, e is unit charge, and the resulting R is in billion volts. If we examine the formula and assume a uniform velocity for particles of any mass, we see that R increases as we go up the atomic scale, since the mass increases faster than does Ze . Then higher mass particles will penetrate deeper into the magnetic field of the earth than will the lower mass particles. A generalized table of composition for galactic cosmic radiation is found in Table 3.

The energy range for these particles ranges from a few Mev up to at least 10^{12} Mev with the average energy in the vicinity of 4×10^3 Mev.

Despite the high energies which the galactic cosmic rays exhibit, there will be little biological hazard during short term missions due to this radiation. On longer missions the situation may change due to the constant accumulation of the radiation.

TABLE 3
COMPOSITION OF GALACTIC COSMIC PARTICLES

<u>Particles</u>	<u>Flux</u> ($R \geq 4.5$ bv)	<u>Percent</u>
Protons	$\sim .77/\text{cm}^2\text{-sec}$	$\sim 84\%$
Alpha Particles	$\sim .11/\text{cm}^2\text{-sec}$	$\sim 14\%$
Carbon, Nitrogen, Oxygen*	$\sim .009/\text{cm}^2\text{-sec}$	$\sim 1\%$
$Z > 10$	$\sim .002/\text{cm}^2\text{-sec}$	$\sim 0.25\%$
Gamma Radiation and Electrons**	---	$\sim 1\%$

* May be a false indication from measurements made in the atmosphere.

** Some space experiments have indicated that larger fluxes of gamma rays and high energy electrons may actually exist in the galactic spectrum.

IV. THE SOLAR WIND

In interplanetary space the surrounding plasma will have some kinetic velocity due to the high temperatures in the corona. At present there is some evidence to suggest that the corona exhibits a "breathing" effect which varies directly with the eleven-year solar cycle period. This seems to be borne out when one observes the density and velocity variations of the plasma flow during minimum and maximum sunspot activity.

During the minimum sunspot activity at the earth's distance from the sun, the mean density of the solar wind is approximately 10^2 particles per cm^3 traveling at a velocity of 500 kilometers per second. This results in an average particle flux of about 5×10^9 particles/ cm^2 sec.

At sunspot maximum the density of particles is expected to increase to approximately 10^4 particles per cm^3 , with a velocity in the vicinity of 1500 kilometers per second. This results in a particle flux at the earth's orbit of about 1.5×10^{12} particles/ cm^2 sec.

The kinetic temperature in the earth's vicinity is approximately $220,000^\circ\text{C}$. However, this will have a very small effect in the heating of vehicles when one considers that the solar radiation flux will amount to about 1.4×10^3 ergs/ cm^2 sec. From an analysis of Mariner II (September-December 1962) data obtained by a plasma probe, plasma energy is approximately 4.4×10^{-9} ergs/ cm^3 .

The solar wind is considered to encompass the earth's magnetosphere and to flow around the outer boundaries much like the wake of a bullet as it passes through air. The magnetosphere is thus flattened on the sunward side of the earth and elongated on the dark side.

Although the flux of particles in the solar wind is high, their energies are relatively low. For this reason, it is expected that the biological radiation hazard behind a small amount of shielding will be insignificant.

V. SOLAR FLARES

Solar flares will undoubtedly be the source of radiation which should concern us most during interplanetary travel. The "great solar bursts" or type 3+ flares emit particles with near relativistic velocities. These particles have energies comparable to the galactic cosmic rays, but their flux is much greater.

Solar flares are associated with the dark spots noted on the photosphere of the sun. The dark spots are local magnetic fields of great intensity. These high magnetic fields inhibit the outward flow of the hot gases from within, and thus cause cooler and darker patches on the

photosphere of the sun. If these areas "collapse" due to the buildup of strong perturbing fields by the ionized gas flowing around the sunspots, then great volumes of ionized gases are spewed out into the chromosphere. This phenomenon is known as the solar flare.

Much of the data presently available, which tells the story of the solar flare, has been accumulated by studies of the various radio wave emissions accompanying the solar flare. The refractive index of an ionized medium is based upon the physical characteristics of the medium itself. The refractive index, μ , of a medium (containing N number of particles with charge e and mass m) to a wave with frequency f is

$$\mu^2 = 1 - \frac{N e^2}{\pi \epsilon_0 m f^2} .$$

Assuming that electrons are the particles affecting the refractive index the most, we may substitute the mass and charge of the electron for m and e . The point at which $\mu^2 = 0$ is the point at which the radio waves will be refracted.

Solving our equation at $\mu = 0$, we find that

$$f = 9 \times 10^{-3} \sqrt{N} \text{ megacycles/second.}$$

This means, that (assuming N increases as we approach the sun) any frequency, f , must have originated at some distance from the sun equal to or greater than the distance of which $f = 9 \times 10^{-3} \sqrt{N}$.

For this reason frequencies ranging from about 300 to 30,000 megacycles/sec are assumed to originate in the chromosphere, whereas lower frequencies are assumed to originate in the corona. As the frequency becomes lower, it must have originated at greater and greater distances from the sun.

Figure 1 illustrates when the specific radio bursts occur and in what frequency range during a solar flare [9, 13]. Table 4 is a summary of the various characteristics of radio emissions from the sun [9].

The flux and energies of the emitted particles are of primary concern when considering the effects of solar flares. It is impossible to make any specific statement as to the flux of particles at the earth from any flare. This is because the flux of particles of a particular energy depends not only upon the characteristics of the flare itself, but also upon the location of the flare on the surface of the sun. In the same sense, the flux of particles is dependent upon the location of the earth as it orbits around the sun.

Anyone who has ever watched a rotating lawn sprinkler can visualize the path which solar particles take as they erupt from the sun (Fig. 2). To an observer in the path of the particles, however, the flux would appear to be traveling in a straight line from the sun.

Table 5 gives the ranges over which the magnitude of the solar flares may be expected to extend. The wide range is necessitated by the variables which may exist.

TABLE 4
CHARACTERISTICS OF SOLAR NOISE

Type	Identifying Characteristics	Source Characteristics	Frequency Characteristics
I	Noise storms usually lasting from hours to days; or bursts of ~ 1 second duration.	Assumed to be of a non-thermal origin, associated with sunspots, "R centers," and sometimes flares.	Less than ~ 250 Mc/sec with bandwidth 1-10 Mc/sec for bursts and 10-100 Mc/sec for continuum. The intensity at 100 Mc/sec $10^{-21} - 10^{-19} \frac{\text{watts}}{\text{m}^2 \text{ c/s}}$
II	Bursts with slow drift of ~ -0.3 Mc/sec ² lasting from 5-10 minutes.	Source is due to plasma oscillations associated with flares. Occurrence begins about 7 minutes after flare. The source moves outward at ~ 1000 km/sec.	Mainly less than 150 Mc/sec with the bandwidth of about 2×10^{-1} of the observed frequency. Intensity at 100 Mc/sec is usually 10^{-20} to $10^{-19} \frac{\text{watts}}{\text{m}^2 (\text{c/sec})}$
III	Bursts with fast drift of ~ 30 Mc/sec ² lasting singly 3-10 sec or in groups of 1-5 minutes.	Assumed to be associated with plasma oscillation associated 50-60% of the time with flares. The source has an outward velocity of $\sim 10^5$ km/sec.	Ranges from > 4000 Mc/sec to < 10 Mc/sec with a bandwidth almost equal to the frequency. The intensity usually is less than $10^{-20} \frac{\text{watts}}{\text{m}^2 (\text{c/sec})}$

TABLE 4 (Cont'd)

Type	Identifying Characteristics	Source Characteristics	Frequency Characteristics
IV	Smooth continuum lasting from minutes to hours.	Source is due to synchrotron radiation. Occurring 70-80% of the time with flares at ~ 15 minutes after start. Initial source velocity ranges from $1-5 \times 10^3$ km/sec for about 10 minutes and then source becomes stationary.	Cover the complete radio band but vary from burst to burst. The bandwidth is frequently several octaves with intensities from 10^{-20} to $10^{-19} \frac{\text{watts}}{\text{m}^2(\text{c/sec})}$.
V	Smooth continuum lasting from 1-2 minutes.	Synchrotron radiation occurring before the maximum of solar flares. The velocity of the source is $\sim 5 \times 10^3$ km/sec.	Frequencies less than 200 Mc/sec with a bandwidth of several Mc/sec at 50-100 Mc/sec. Intensities 10^{-20} to $10^{-19} \frac{\text{watts}}{\text{m}^2(\text{c/sec})}$.
Micro-wave	Continuum and bursts lasting 0.5 to 20 minutes.	Assumed to be of synchrotron and possibly thermal origin associated about 80% of the time with flares.	The frequency range is $\sim 1000-20,000$ Mc/sec with a bandwidth of several octaves. The intensity is usually $\sim 5 \times 10^{-22}$ to $5 \times 10^{-20} \frac{\text{watts}}{\text{m}^2(\text{c/sec})}$ at 3000 Mc/sec.

TABLE 5 (Ref. 6)

PARTICLE RADIATION DUE TO SOLAR FLARES

Flux	Range from 3×10^3 to $1.2 \times 10^4/\text{cm}^2$ sec-ster distributed isotropically, and containing predominantly H^+ particles.
Energy	Range from ~ 10 Mev to ~ 500 Mev.
Duration	From 10 to 100 hours.
Origin	Associated with class 3 or greater flares, which follow the solar cycle: $\sim 12/\text{yr}$ at solar maximum to $\sim 3/\text{yr}$ at solar minimum
Dose	Depending upon flux and energy ranges from 10^{-3} rad to 10^3 rad.

VI. SPECTRAL IRRADIATION

Of all the radiation hazards which will be encountered in space, the effects of spectral irradiation are the most difficult to analyze at the present time. This is true because of the difficulty in studying the solar photon flux in this most important range below 3000 Å. Since radiation of wavelengths less than 3000 Å is strongly absorbed by our atmosphere, earth-bound studies in this range are mostly hypothetical. Artificial sources of photon flux in the X- and γ -ray range have been studied and may inform us as to the hazards which may be encountered.

In the region from about 2200 Å to 2900 Å, atmospheric ozone absorbs almost all the photon radiation. From about 900 Å atmospheric oxygen above 75 km absorbs the radiation, and below 900 Å many atmospheric constituents share in absorbing radiation.

Table 6 summarizes the percent of solar electromagnetic energy radiated in various wavelength intervals [4]. Figure 3 illustrates the wavelength spectrum from the sun, and Figure 4 is a corresponding frequency graph [12].

TABLE 6

<u>Wavelength Å</u>	<u>Percent of solar Electromagnetic Energy</u>
< 2000	0.2
2000 - 3800	7.5
3800 - 7000	41.0
7000 - 10000	22.0
10000 - 20000	23.0
> 20000	6.0

The most hazardous region of the electromagnetic spectrum is the short wavelength X-ray range. Fortunately, the most predominant energy region is not in this range.

The X- and γ -radiations increase as solar flares occur. The following table lists the X-ray fluxes detected by rocket-borne equipment.

TABLE 7

	Date	2-8 Å ergs/cm ² sec	8-20 Å ergs/cm ² sec	44-60 Å ergs/cm ² sec
Background and Bright Surge	7-24-59	1.3×10^{-2}	9×10^{-2}	0.15
Background	8-7-59	0.1×10^{-2}	2.3×10^{-2}	----
Background	8-14-59	0.1×10^{-2}	2.3×10^{-2}	0.075
Background	8-29-59	0.33×10^{-2}	----	0.17
Flare 2+	8-24-59	2.6×10^{-2}	16×10^{-2}	< 0.41
Flare 2+	8-31-59	3×10^{-2}	90×10^{-2}	< 1.8
Flare 2+	9-1-59	$> 8.8 \times 10^{-2}$	$> 90 \times 10^{-2}$	----

From most of the data presently available, it appears that the spectral component of radiation need not be considered. The effects of the electromagnetic radiation on the eyes are apparent.

VII. CONCLUSIONS

From the preceding sections it is apparent that Van Allen and solar flare radiations need be of primary concern during space flight. A long duration earth orbit, as well as an extended extraterrestrial mission, must be adequately protected against the harmful radiations which each will encounter.

In the case of an extended earth orbit where the radiation dose may be accumulated over a period of time, the obvious solution is to have the personnel periodically replaced and sensitive instrumentation adequately protected. By a frequent replacement of personnel, the dose will not have time to accumulate to serious proportions. Such an arrangement would obviously be required for a manned orbiting space station or orbiting laboratory. This might become troublesome to the people working on a specialized problem to which they have become dedicated, or to persons working in intricate areas where several people would have to be trained in one specialized area. Other than these human factors, the problems involved do not appear too difficult.

On an extended extraterrestrial mission, personnel cannot be replaced as they acquire a specific minimal amount of radiation. One solution to this problem might be to fractionate the dose. Assuming complete shielding for the entire vehicle will not in itself be sufficient to cope with any situation, it may be more realistic to provide an area which has sufficient shielding to cope with any radiation hazard. Each member of the crew would be required to spend a certain portion of his time in this area. During solar flares perhaps all members of the crew could remain in this area for a short period of time (about three to four hours).

Such an arrangement is obviously to be included for conservation of shielding weight. The engineering problems encountered may be a bit more complicated, but nothing which cannot be overcome.

At the present time very little is known of the effects of radiation on the human body, especially the effects which exposure to radiation may impose upon future generations. In addition, sensitive vehicle instrumentation - especially items concerned with the guidance and control systems and the spacecraft life systems - must be adequately tested to establish limits of radiation exposure so that this equipment may be protected from possible excess.

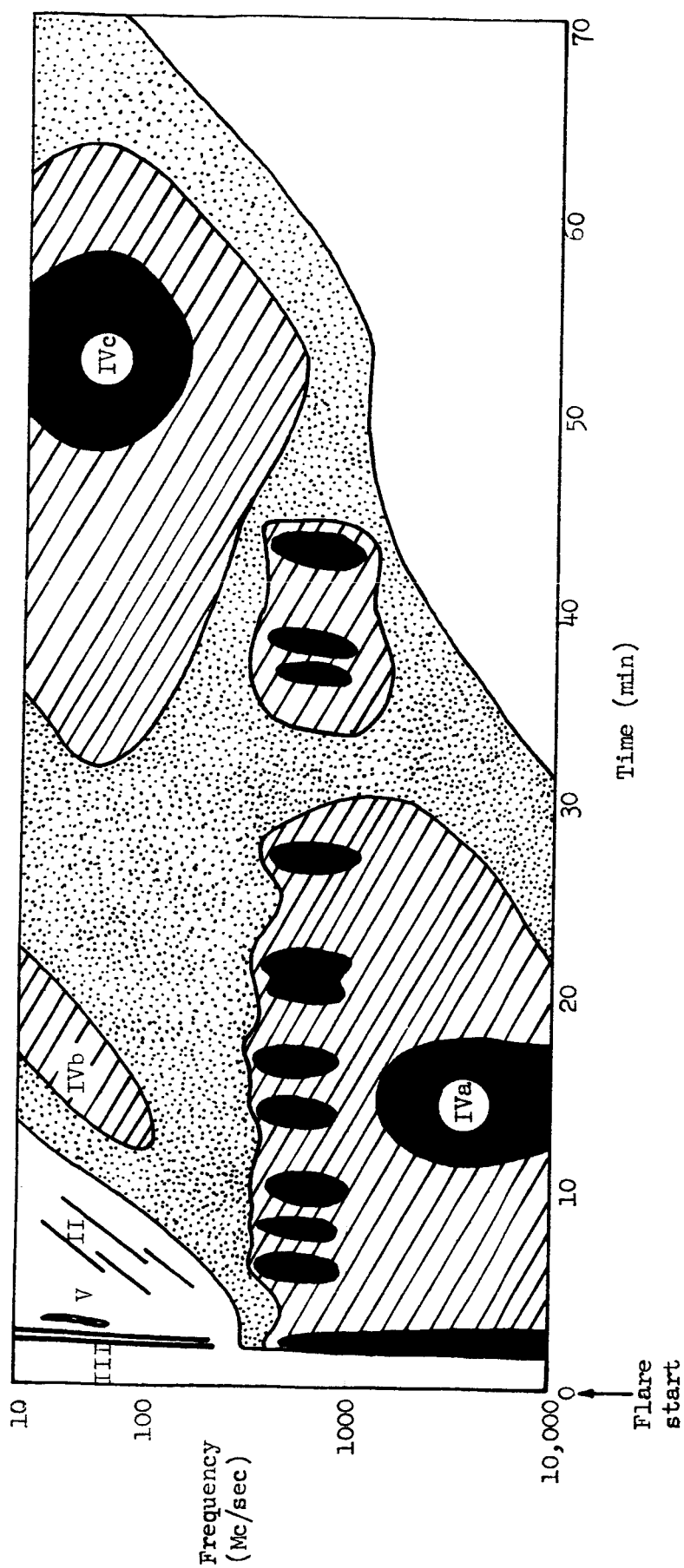


Figure 1. Time-Radio Frequency Diagram of a Solar Flare
(see Table 4)

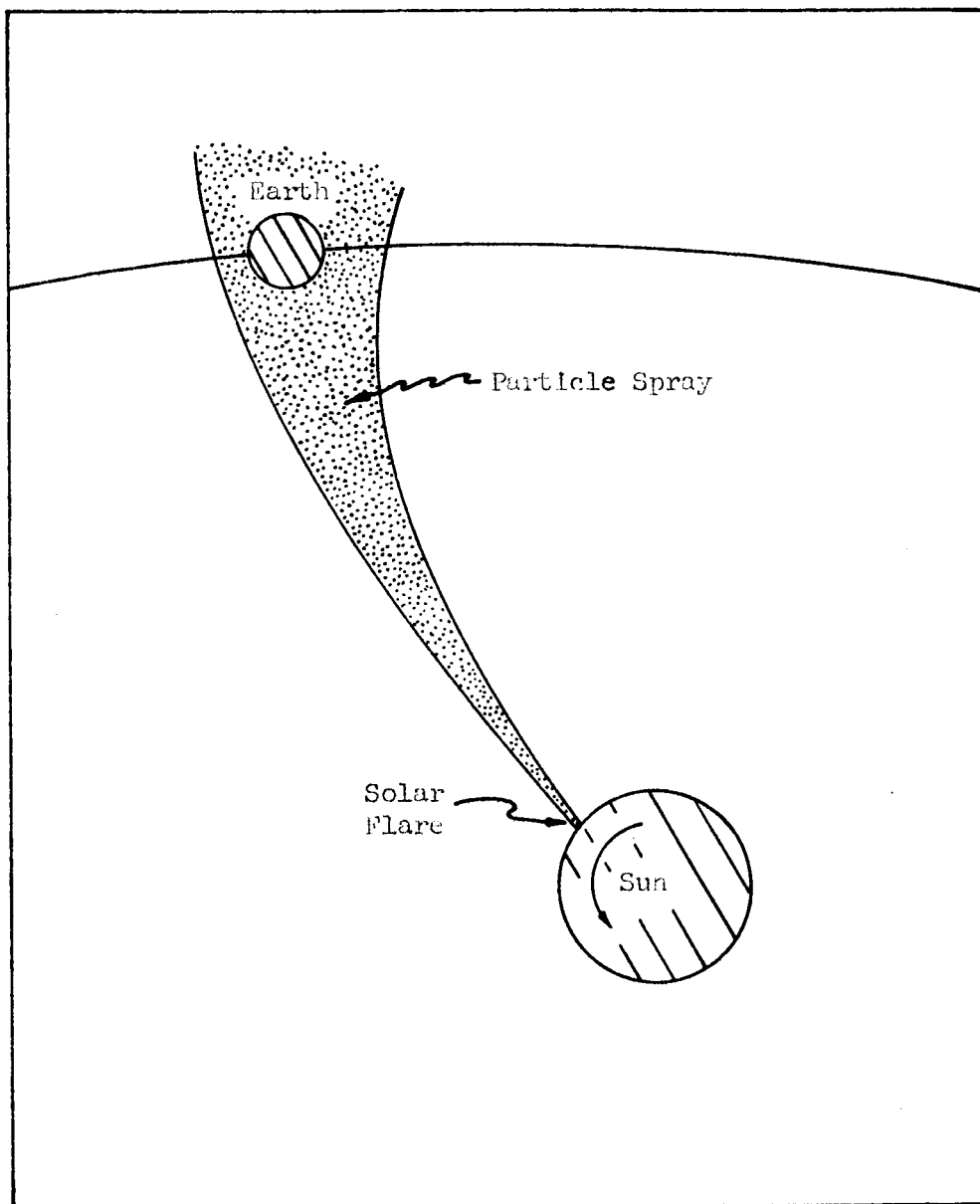


Figure 2. Path Along Which Particles From the Sun Following A Solar Flare Travel, As Seen From Above the Plane of the Ecliptic

THE ELECTROMAGNETIC SPECTRUM

1 ANGSTROM (\AA) = 10^{-10} METERS = 10^{-4} MICRONS (μ)

1 ELECTRON VOLT = 1.602×10^{-12} ERGS

QUANTUM ENERGY = $h\nu$

WHERE h IS PLANCK'S CONSTANT (6.625×10^{-27} ERG SEC OR
 4.134×10^{-15} ELECTRON VOLT SEC.

ν IS FREQUENCY IN CYCLES PER SECOND.

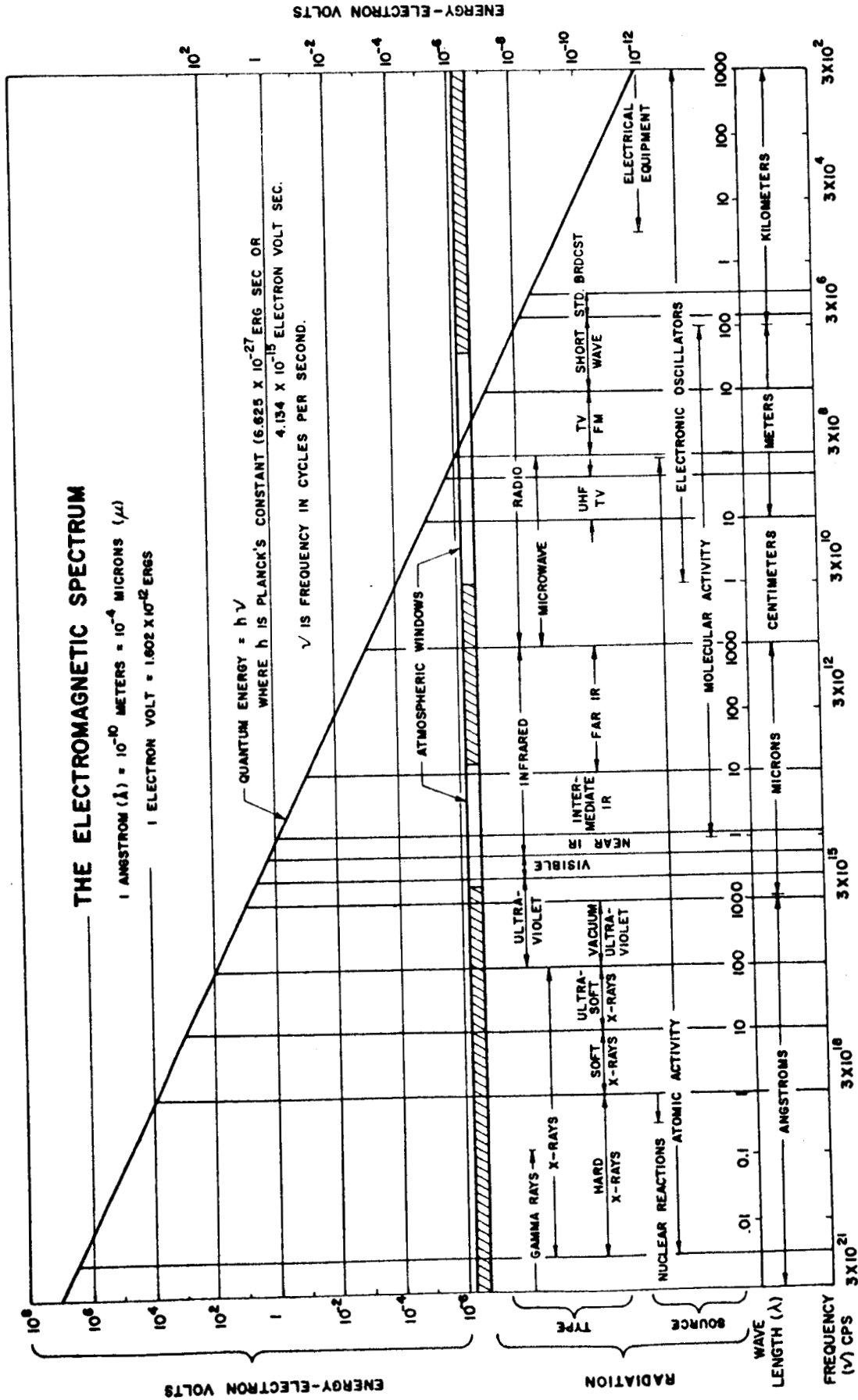


FIGURE 4. ELECTROMAGNETIC SPECTRUM DEPICTING SOURCE AND TYPE OF EACH OF THE VARIOUS CLASSIFICATIONS OF WAVELENGTHS

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ATTN: Tech Library, Mrs. Russell